Comparison of durability indicators obtained by Non Destructive Testing methods to monitor the durability of concrete structures

Géraldine Villain, Jean-Paul Balayssac, Vincent Garnier, Bogdan Piwakowski, Jean Salin, Vincent Fardeau, Xavier Dérobert, Odile Coffec, Anaëlle Joubert

COMPARISON OF DURABILITY INDICATORS OBTAINED BY NON DESTRUCTIVE TESTING METHODS TO MONITOR THE DURABILITY OF CONCRETE STRUCTURES

G. Villain[1], J-P. Balayssac[2], V. Garnier[3], P. Piwakowski[4], J. Salin[5], V. Fardeau[6], X. Dérobert[1], O. Coffec[1], A. Joubert[1]

[1] *IFSTTAR Nantes, Route de Bouaye, CS4, 44344 Bouguenais cedex, France*
[2] *Université de Toulouse, UPS, INSA, LMDC, Toulouse, France*
[3] *Université de la Méditerranée, LCND-LMA, Aix-en-Provence, France*
[4] *Université de Lille, Ecole Centrale de Lille, Villeneuve d'Ascq, France*
[5] *EDF R&D Chatou, France*
[6] *CEREMA DTITM (ex SETRA), Sourdun, France*

geraldine.villain@ifsttar.fr

ABSTRACT

This paper deals with the use of non destructive testing methods (NDT) to assess indicators of concrete durability and mechanical properties of reinforced concrete structures.

On site, NDT methods based on electromagnetic or ultrasonic wave propagation (such as radar, impact echo, ultrasonic transmission device…) are used because they are more or less sensitive to water content and mechanical properties depending on the method. It has been shown, in a former project [1, 2], that the NDT results called "observables" are linked to mechanical and durability indicators (Young's modulus, compressive strength, porosity and saturation degree). Meanwhile, the relationship between observables and indicators depends on the concrete mix design. A calibration protocol is then proposed to get this relationship for the right mix of the reinforced structure studied by using a minimal number of cores. The cores are non-destructively characterised in laboratory or used to determined reference indicators by standardised destructive methods.

The aims of this paper are first to present the ND calibration protocol on cores and then to validate this proposed calibration protocol. To achieve this goal, some NDT results obtained on site and on the corresponding core are compared and durability indicators deduced from NDT calibration are compared with reference durability indicators.

KEYWORDS: *porosity, water content, compressive strength, NDT, radar, ultrasonic method.*

INTRODUCTION

In civil engineering, it is important that non destructive testing (NDT) becomes a useful tool for engineers and structure owners to get quantitative indicators, to establish precise diagnosis and to monitor the structure conditions during its service life.

The study presented herein is a part of a French research project (C2D2-ACDC) of the urban and civil engineering network of the Ministry of Ecology and Sustainable Development. The aims of the project is namely to transfer the use of NDT from laboratory to real structures [3].

This study deals with assessing concrete mechanical properties and durability indicators (such as porosity or water content), key-parameters for physico-chemical degradations and rebar corrosion of reinforced concrete structures [4]. The mechanical and durability indicators studied are the compressive strength *Rc*, the Young's modulus E_{stat}, the bulk porosity ϕ and the degree of saturation *S*. Here, we focus on 2 indicators ϕ and *S*.

Concerning NDT, methods using ultrasonic (US) wave are mainly sensitive to mechanical properties or porosity [5-9], whereas methods based on electromagnetic (EM) wave or electrical field determination are highly sensitive to water content [10-13]. However, US methods are also sensitive to water content and, to a lesser extend, EM methods to porosity. As a consequence, a combination of complementary methods is recommended to accurately assess the degree of saturation and the porosity of concrete [14-15, 2]. The results of NDT are called "observables" (wave velocity, dielectric permittivity, dynamic Young's modulus, resistivity…). These observables are linked to indicators by relationships depending on the concrete mix design. Thus, we propose a calibration protocol to determine the relationships between observables and indicators on a small number of cores taken from the studied structure.

The first part of this paper presents the three complementary NDT methods, which allow us to test cores (∅75x70 mm) in the laboratory. The second part is devoted to the calibration protocol. The last part aims to compare laboratory and site test results, as well as the different calibration relationships obtained during a former project, and finally estimated indicators are compared to reference ones in order to validate the protocol. The concerned site test is a highway bridge in Marly (France).

1 ND METHODS USED FOR CALIBRATION IN THE LABORATORY

Three lab ND methods were designed to characterize cylindrical samples of the same size: diameter equal to 75 mm and height to 70 mm. These dimensions have been chosen greater than 3 times maximal diameter of currently used aggregates (20 mm) in order to dispose of representative elementary volume of a heterogeneous material such as concrete.

1.1 Ultrasonic waves in transmission

The US device, developed by [16], enables to measure in transmission the velocity of compression (P) or shear (S) waves, whose central frequency is equal to 250 kHz. This device (Fig. 1) is composed of an amplifier-generator, 2 concentrical transducers P and S, an amplifier for the transmitted signal and an oscilloscope. For each sample, the mean signal (256 repetitions) is recorded 10 times in 10 different positions. The observables obtained are the P-Wave velocity *Vp* and the S-wave velocity *Vs*. Knowing the sample density, the dynamic Young's modulus and Poisson's ratio can also be calculated.

Note that the P-wave velocity *Vp* can be compared to P-wave velocity measured by transmission at the same frequency on site.

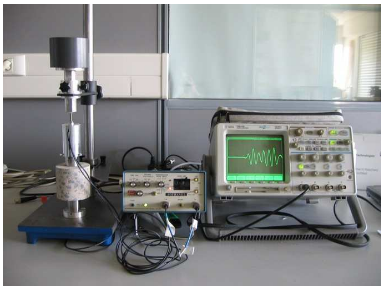


Figure 1: US transmission device

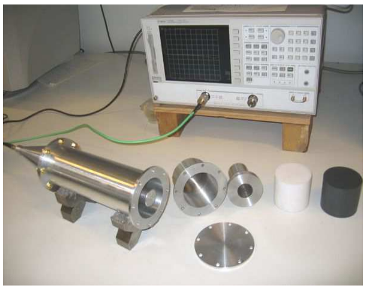


Figure 2: EM coaxial cell

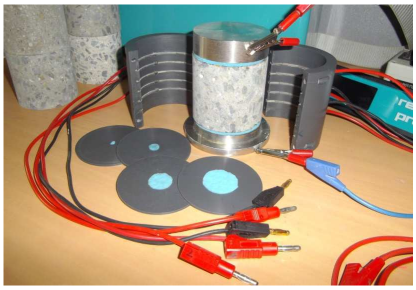


Figure 3: Resistivity cell

1.2 Electromagnetic coaxial cylindrical cell

An EM cylindrical cell has been designed for the EM characterization of hydraulic and bituminous concrete [17]. It enables us to determine the complex dielectric permittivity in the frequency bandwidth of the existing radar (GPR) devices from 50 to about 1200 MHz. A coaxial cylindrical transmission line (cell and cables) connected to a vectorial network analyzer has been designed (Fig. 2). An iterative inversion procedure (Newton-Raphson method) retrieves the material complex permittivity from the reflection coefficient measurements. The dispersion curve of the complex permittivity is thus calculated.

The extracted observable is the real part of the relative permittivity $Eps=\varepsilon_{r\_800MHz}$ (called here permittivity) at 800 MHz corresponding roughly to the observable obtained on site with the 1.5GHz GPR antennas [12].

1.3 Electrical multi-electrode cell

An electrical resistivity cell has been designed to measure the resistivity of cylindrical concrete samples [18]. Alternating current is injected on the 2 planar surfaces and 5 annular electrodes enable us to measure the potential difference between 2 electrodes corresponding to the sample resistivity at different heights (Fig. 3). Either the local at different positions or the global average resistivity of the concrete sample is determined.

The mean value (noted Re) constitutes the similar observable as the concrete resistivity measured on site thanks to the 10-cm spacing quadripole used on site by a partner laboratory [19].

2 CALIBRATION PROTOCOL

After a rapid first ND testing, called "pre-auscultation", in particular with US on-site techniques (impact echo for instance [2]), zones for coring are chosen such as the minimal and maximal mechanical characteristics are reached. Namely, the wider is the gap, the more accurate is the evaluation of the slope of the calibration regression line. The third zone can be chosen with intermediate properties. The cores are carefully wrapped in sealed plastic bags.

- Phase 0: In the lab, the initial mass is measured to be able to estimate the initial saturation degree.
- Phase 1: The samples are saturated with water under vacuum [20], weighted in air and in water, then ND tested.
- Phase 2: The samples are dried in a climatic chamber under controlled conditions (around RH=80% and T≤65°C) for several days until constant mass. They are then weighted and ND tested.
- Phase 3: The samples are dried in a climatic chamber under controlled conditions (around RH=50% and T≤65°C) for several days until constant mass. They are then weighted and ND tested.
- Phase 4: The samples are dried in an oven at T=105°C for several days until constant mass to get the dry mass and be able to determine the sample bulk porosity [20].

This protocol is summarized in Fig. 4.

The aim of phases 2 and 3 is to reach a degree of saturation around S=75% and S=50%, but, as the desorption isotherm linking the relative humidity RH and S for a specific concrete mix, is not available only a rough approximation of RH is possible.

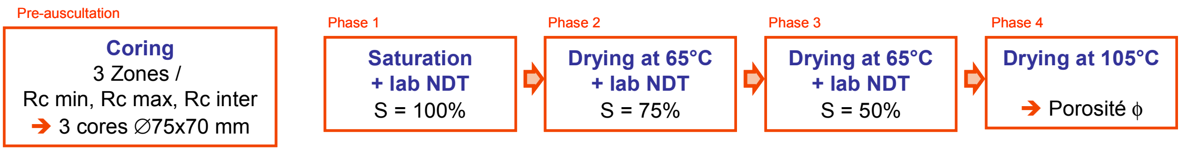


Figure 4: Scheme of the calibration protocol

3 APPLICATION ON A TEST-SITE: PILES OF A HIGHWAY BRIDGE IN MARLY

The protocol developed during the research project C2D2-ACDC has been tested on two sites:
- on three piles of a highway bridge located in the north of France (Marly), and
- on three walls of security leak tanks of a power plant near the sea side (Le Havre).

The results used in this paper are only coming from the experimental campaign led on the highway bridge of Marly.

The tested structure is a triple highway bridge (Fig. 5) situated in the north of France in the suburb of Valenciennes and it is called Marly's bridge. Three different piles were tested with ND on-site methods [3]. After NDT, cores were taken where NDT had been performed then sawn into slices. The ND lab protocol described herein was applied on 15 samples (∅75x70 mm): 3 from pile Sadam, 3 from pile S, 5 from pile ZBL, all taken in the core of the pile (safe concrete), and 4 additional samples from pile ZBL taken at the surface (cover concrete submitted to degradations). Moreover, a large number were characterized by reference standardized destructive tests: compressive strength R_c [21], static Young's modulus E_{stat} [22], porosity ϕ and degree of saturation S [20].

a b
Figure 5: Marly's bridge: a – Global view – b – Zoom on S-pile

4 RESULTS AND DISCUSSION

In this part, the results following the ND lab protocol are presented.

4.1 Calibration curves

The ND lab protocol enables to determine different calibration curves, among which are presented:
- the US P-wave velocity vs. porosity in Fig. 6,
- the US P-wave velocity vs. degree of saturation in Fig. 7,
- the EM permittivity at 800 MHz vs. degree of saturation in Fig. 8,
- the electrical resistivity vs. degree of saturation in Fig. 9,

for the 3 piles of Marly's bridge (Sadam in red, ZBL in black and S in blue).

During a former research project (ANR-SENSO [1, 2, 9]), some relationships between observables and indicators were determined. We choose to compare the calibration curves obtained for Marly's bridge to these relationships obtained in laboratory on slabs (8 per concrete) by using on-site ND techniques. The ANR-SENSO results are presented in green in Fig. 6 to 9 for two concretes G3a and G7 whose water-to-cement ratio and compressive strength are similar to that of Marly's bridge (see Table 1).
One of the main conclusions of ANR-SENSO project is that US velocity Vp is linearly correlated with porosity. It seems confirmed for the cores of Marly's bridge with ND-lab technique, with a similar slope (Fig. 6a), even if the results are highly dispersed. It is more difficult to get very different porosities for a same concrete mix on a real structure (reason of minimal and maximal chosen zones) than in the lab for 8 mixes with different water-to-cement ratio from 0.3 to 0.9.

Moreover, the uncertainty of porosity determination [4] on 3 cores is about 0.5%-1% which is not far from the width of Marly's core porosity (from 14.1 to 16.3%). Another interesting result is that the surface samples show the same slope (dotted black line) as the others. The decrease of their P-wave velocity can be due to skin effect, for example the effect of cover concrete carbonation.

Table 1: Concrete mix designs and properties under saturated conditions (sat)

		G3a	G7	Bridge piles
Aggregate type	(kg/m^3)	SR 14	SR 14	?
Aggregate size 4-14 or 4-22	(kg/m^3)	1069	1047	?
Sand 0-4	(kg/m^3)	774	839	?
Cement CEM I 52.5 N Calcia	(kg/m^3)	370	320	?
Total water	(kg/m^3)	211.6	216.3	?
Water-to-cement ratio	$W/C(-)$	0.57	0.68	?
Compressive strength	Rc_{sat} (MPa)	40.5±1.5	38.3±3.0	50.1±5.9
Static Young's modulus	E_{sat} (GPa)	27.9±0.4	27.4±2.8	32.0±2.7
Mean density of the slab/core	ρ_{sat} (kg/m^3)	2447±7	2455±12	2368±27
Bulk porosity	ϕ (%)	16.0±0.7	15.9±0.8	15.7±0.7

These results also confirm (Fig. 6b) that the P-wave velocity Vp is linearly correlated to the degree of saturation in the range 45% ≤ S ≤ 100%, with a similar slope.

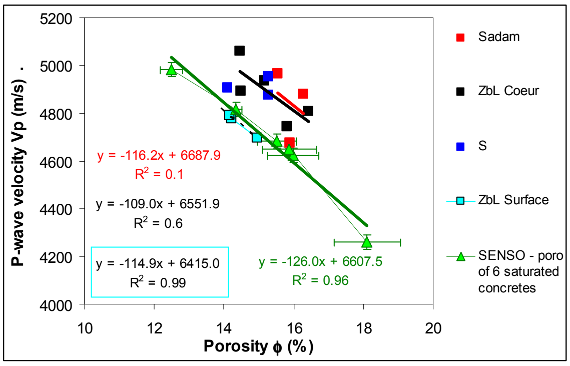


Figure 6: P-wave velocity vs. porosity for Marly's cores and SENSO slabs

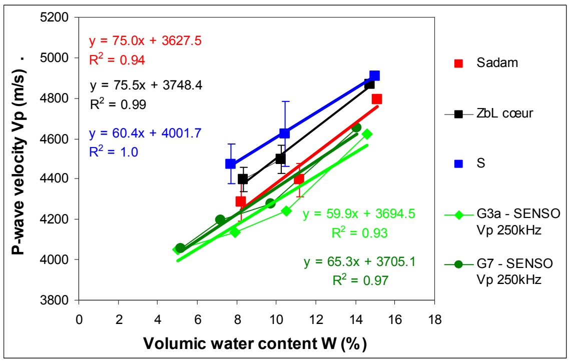


Figure 7: P-wave velocity vs. water content for Marly's cores and SENSO slabs

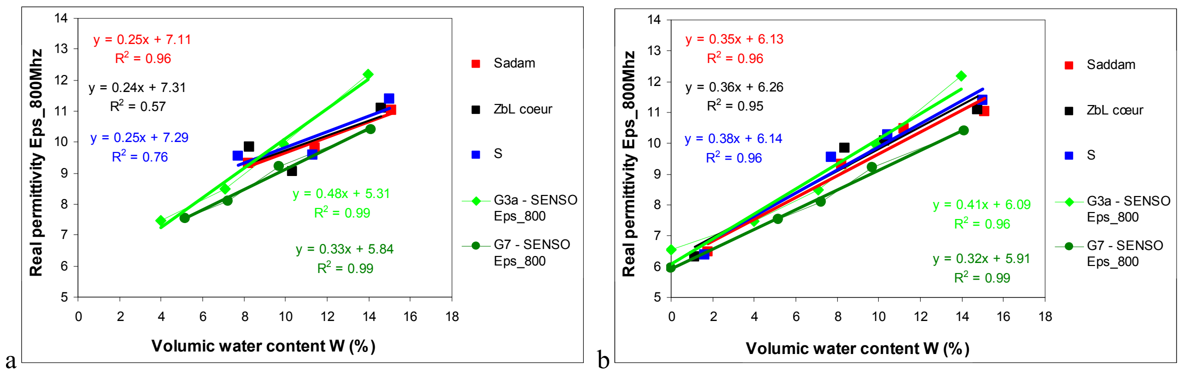
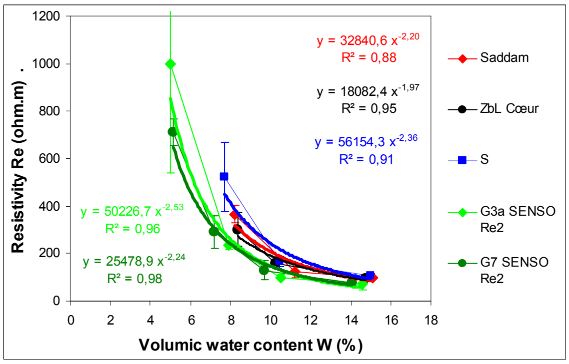


Figure 8: Permittivity at 800 MHz vs. water content for Marly's cores and SENSO slabs
a – In the range 40% ≤ S ≤ 100% – b – In the range 0% ≤ S ≤ 100%

Concerning the EM permittivity, the results obtained on Marly's bridge cores with the ND-lab technique (EM cell) are comparable to results obtained on SENSO slabs with the on-site techniques.

As the uncertainty was greater than expected (Fig.8a), an intermediate phase was added: before drying at T=105°C, which destroys a part of the hydrates, the samples have been dried at T=65°C in an oven until constant mass, then ND tested. It enables to perform the ND test at very lower water content and to improve the accuracy of the linear regression as can be seen in Fig. 8b.

Concerning the electrical resistivity, the results obtained on Marly's bridge cores with the ND-lab technique (resistivity cell) are comparable to results obtained on SENSO slabs with the on-site technique (Fig. 9). Nevertheless, resistivity measurement is highly sensitive to chemical changes due to different hydration of the skin or to degradation like carbonation. The resistivity cell developed in IFSTTAR [18] is able to determine resistivity gradients from the surface to the core of the structure as it is shown by Fig. 10, where the point numbers can be assimilated to depths. Therefore, on site, this technique has to be very carefully analyzed.



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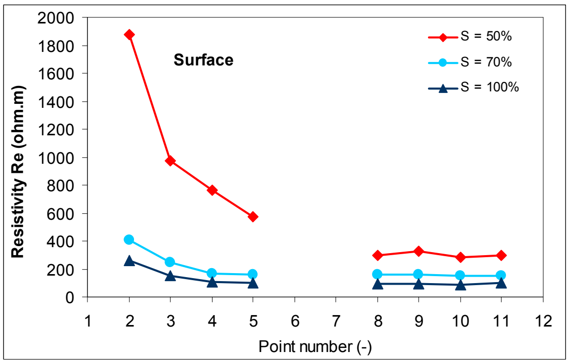

b

Figure 9: Resistivity vs. water content for Marly's cores and SENSO slabs

Figure 10: Resistivity of pairs of annular electrode for a ZBL core situated near the surface or in the core

4.2 Use for estimation of durability indicators on site

These calibration curves can be used to estimate the durability indicators (here porosity and degree of saturation) thanks to the ND observables determined on Marly's bridge with on site methods. For each observable (Vp, Eps, Re), a double linear regression depending on porosity and degree of saturation can be calculated by using ND-lab results as explained in [2]. Then, the corresponding NDT observables obtained on site enable to assess the durability indicators. Table 2 shows the estimated values and the values measured with reference standard destructive methods performed on cores in laboratory. We choose to compare the results in the meshes where NDT on site and cores were taken (same mesh except for the pile Sadam where it is impossible). As the reference measurements obtained in one lab (IFSTTAR) were used to determine the calibration curves, the comparison is made on reference values obtained in another lab (LMDC) to be independent.

Table 2: Comparison of estimated durability indicators by using on site NDT and calibrations with reference durability indicators measured on cores

	Localization on site		Mean estimations ± standard deviation		Ref. measurements on cores	
Pile	NDT	Coring	ϕ (%)	S (%)	ϕ (%)	S (%)
ZBL	1 mesh (Vp ; Eps ; Re)	1 core in the same mesh, ref. LMDC	15.5	81.3	15.2	72.3
ZBL	5 meshes (Vp ; Eps ; Re)	5 cores in the same mesh, ref. IFSTTAR	15.3 ± 0.4	79.8 ± 1.5	15.3 ± 0.8	73.1 ± 2.8
Sadam	3 meshes (Vp ; Eps)	2 cores in the adjacent mesh, ref. LMDC	15.4 ± 0.3	78.2 ± 3.4	15.7 ± 0.4	76.1 ± 0.2
S	3 meshes (Vp ; Eps)	3 cores in the same mesh, ref. LMDC	16.9 ± 3.9	68.2 ± 6.8	16.1 ± 1.2	75.1 ± 1.9

In table 2, the estimated and measured indicators are roughly close. The measurement of resistivity enables to correct the porosity estimated values: using 3 observables increases the accuracy. On the other hand, we observe that the estimated degree of saturation is higher than the measured one. This can be due either to the conditions of coring and core conservation, or to the difference between the surface and the core of the pile concrete. The surface is namely submitted to precipitations and degradation which induce gradients and chemical changes and thus also induce a difference between on site surface measurements of resistivity and permittivity. In this study, the calibration curves are determined only on core samples.

CONCLUSION

A protocol of calibration is proposed to analyse on site NDT measurements and to obtain durability indicators such as porosity and water content. In the same way, compressive strength and saturation degree can be assessed. A comparison of estimated indicators and measured ones by using standard destructive methods validates this protocol.

Finally, the analysis of the results shows that the calibration protocol is useful to evaluate correctly the global mechanical and durability indicators and to assess the concrete conditions of the tested structures. However, it also underlines that further researches are needed to better take into account the gradients of properties in the cover concrete due to skin's effects, drying or penetration of aggressive agents.

As this complete efficient protocol in laboratory takes quite a long time, numerical corrections are also proposed in [3].

Moreover, recommendations concerning ND auscultation and analysis in view of durability assessment of reinforced concrete structures are proposed in C2D2-ACDC project [23].

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